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INTRODUCTION

The grant, NASA NGL-05-007-190 has supported theoretical research on many topics in space plasma physics over its more than twenty years: spatial transport, plasma waves, pitch angle diffusion in the earth's and Jupiter's radiation belts, instabilities and turbulence in the equatorial and auroral ionospheres, magnetospheric substorms, magnetic reconnection at the nose and tail of the earth's magnetosphere, physics of the Io torus, collisionless shock waves, nonlinear plasma waves and particle acceleration are a few examples. NASA has supported the Ph.D. research of (in order of time) Joseph Kindel, Kenneth Lee, Lawrence Lyons, Morrell Chance, Mary Hudson, David Barbosa, Stephen Gayer, F. Stanley Fujimura, William Lotko, Kevin Quest, John Engel, Pat Edmiston, Tohru Hada, Willis Livesey, and Stewart Moses -- a list notable for the number who continue to contribute to the progress of space plasma physics. Three of this list are fellows of the American Physical Society, two are fellows of the American Geophysical Union, and Mary Hudson and Kevin Quest have won the AGU's Macelwane award for outstanding achievement before age 35. This grant also supported the post-doctoral research of UCLA research scientists, James Maggs and David Barbosa, UCLA professor Maha Ashour-Abdalla, and Professor Tohru Hada, of the University of Kyushu, Japan, who contribute now to space research under separate support.

This final report illustrates the nature of the research supported by NGL-05-007-190 over many years by summarizing the status of the research problems that were under consideration when the grant came to an end in 1988. The papers cited in the text were supported, wholly or in part, by the grant. We include selected reprints.

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CRITICAL MACH NUMBERS IN COLLISIONLESS SHOCK WAVES

The standard approach to estimating the critical fast shock Mach numbers at which ion reflection is required to provide the necessary dissipation comes from classical Navier-Stokes Magnetohydrodynamics, where we ask when resistivity fails to produce the needed shock dissipation, and ion dissipation is required. The paper below estimated the rigorous dependence of the critical Mach number upon upstream shock parameters.

Edmiston, J.P., and C.F. Kennel, "A Parametric Survey of the First Critical Mach Number for a Fast MHD Shock", J. Plasma Physics 32, 429, 1984.

However, this approach presumes that anomalous resistivity is already present. Observations of ion acoustic and lower hybrid turbulence in subcritical shocks have so far failed to provide conclusive evidence that this presumption is correct for the earth's bow shock. For this reason, W.A. Livesey's research, supported by this grant, which suggests that ion reflection does set in at the resistive critical Mach number, is puzzling.

W. A. Livesey, C. F. Kennel, and C. T. Russell, "ISEE-1 and -2 Observations of Magnetic Field Strength Overshoots in Quasi-Perpendicular Bow Shocks", Geophys. Res. Lett., 9, 1037, 1982 (4 pages)

W.A. Livesey, C.T. Russell, and C.F. Kennel, "A comparison of Specularly reflected gyrating ion orbits with observed shock foot thicknesses", J. Geophys. Res., 89, 6824, 1984, (4 pages).

The following paper, which was partially supported by this grant reviews the above results:

C. F. Kennel, J. P. Edmiston, and T. Hada, "A Quarter Century of Collisionless Shock Research", pp. 1-36, in "Collisionless Shocks in the Heliosphere: A Tutorial Review", (R. G. Stone and B. T. Tsurutani, eds.), Geophysical Monograph 34, American Geophysical Union, Washington, 1985.

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The classical resistive critical Mach number on which both the theory and experimental results are based might not be the right one. Perhaps it is better to use a slightly higher critical Mach number, in which resistivity and thermal conduction are taken into account. This question was the subject of research completed in 1987. C.F. Kennel published one paper on Critical Mach numbers in 1987, and one in 1988.

C.F. Kennel, "Critical Mach Numbers in Classical Magnetohydrodynamics", J. Geophys. Res., 92, 13,427, 1987.

Kennel, C.F., "Shock Structure in Classical Magnetohydrody-namics," J. Geophys. Res., 93, 8545, 1988.

In brief, the above papers define a new "resistive-thermal" critical Mach number for fast and slow shocks, and investigate the structure of the supercritical shocks.

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SLOW SHOCKS

The basic properties of slow shocks were discussed in three papers. The first, below, discusses the conditions in which nonlinear slow waves are expected to steepen and form shocks:

Hada, T., and C.F. Kennel, "Nonlinear Evolution of Slow Waves in the Solar Wind," J. Geophys. Res., 89, 531, 1985.

The next surveys the properties of the Rankine-Hugoniot solutions for slow shocks. It is hard to believe, but properties of slow shocks have not been surveyed in a systematic fashion. The discovery of slow shocks in the earth's magnetic tail by ISEE-3 makes such a survey timely.

Edmiston, J. P., and C. F. Kennel, "A Parametric Study of Slow Shock Rankine-Hugoniot Solutions and Critical Mach Numbers," J. Geophys. Res., 91, 1361, 1986 (12 pages).

The following paper reviewed the results of the above two papers.

Kennel, C.F., "Fluid Theories of Slow Shock Structure," Proceedings of the Sixth International Solar Wind Conference, 357, National Center for Atmospheric Research, Boulder, Colorado, 1988.

SWITCH-ON SHOCKS

We assembled basic information from fluid theory about nonlinear wave steepening and critical Mach numbers in order to stimulate searches in space of switch-on shocks, and to motivate numerical simulations of them.

C.F. Kennel and J.P. Edmiston, "Switch-on Shocks", J. Geophys Res.,93, 11,363, 1988

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QUASI-PARALLEL SHOCKS, MHD TURBULENCE AND PARTICLE ACCELERATION

Kennel reviewed our understanding of quasi-parallel shocks at a symposium held at the International Centre for Theoretical Physics in Trieste, at the COSPAR meeting in Toulouse, and at the International Rosenbluthsymposium.

Kennel, C.F., "On the Relationship between Collisionless Shock Structure and energetic particle acceleration", in Radiation in Plasmas, Proceedings Spring College on Radiation in Plasmas, p. 87, International Centre for Theoretical Physics (Trieste), World Scientific Publishing Co., Singapore, 1984, (16 pages).

C.F. Kennel, "Quasi Parallel Shocks", Adv. Space Res., 6, 5, 1986

Kennel, C.F., "Cosmic Ray Acceleration: A Plasma Physicist's Perspective", pp. 203-226, in From Particles to Plasmas, Lectures Honoring Marshall N. Rosenbluth (J.W. Van Dam, ed.) Addison-Wesley, N.Y., 1989.

In brief, superthermal ions heated by the shock propagate upstream, destabilize long wavelength Alfven turbulence, which in turn scatter the ions back and forth across the shock. The ions gain energy by the first order Fermi-Mechanism. The Alfven waves are blown through the shock into the downstream region. It is thought that this network of processes, when it occurs at interstellar shocks created by supernovae, accelerates the galactic cosmic rays.

A tight chain of astrophysical arguments indicates that the interstellar shocks will have Mach numbers similar to those in interplanetary space, and that the parameters of the interstellar plasma are similar enough to those of the solar wind to make the study of solar system shocks pertinent to the cosmic ray acceleration problem. We will never be able to detect the microprocesses occurring in interstellar shocks. Thus solar system shocks are not only interesting in their own right, but they are also our best chance to study the microphysics of particle acceleration by shocks.

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Our approach to the problem of shock acceleration is both observational and theoretical. On the observational side, Kennel (1984 a, b, 1986) subjected the interplanetary shock of Nov. 11-12 1978 to extensive study, ultimately comparing it with Lee's (1983) theory of ion acceleration by interplanetary travelling shocks.

Kennel, C.F., F.L. Scarf, F.V. Coroniti, C.T. Russell, K.P. Wenzel, T.R. Sanderson, P. Van Nes, W.C. Feldman, G.K. Parks, E.J. Smith, B.T. Tsurutani, F.S. Mozer, M. Temerin, R.R. Anderson, J.D. Scudder, M. Scholer, "Plasma and Energetic Particle Structure Upstream of a Quasi-Parallel Shock", J. Geophys. Res., 89, 5419, 1984 (16 pages).

Kennel, C.F., J.P. Edmiston, F.L. Scarf, F.V. Coroniti, C.T. Russell, E.J. Smith, B.T. Tsurutani, J.D. Scudder, W.C. Feldman, R.R. Anderson, F.S. Mozer, and M. Temerin, "Structure of the Nov. 12, 1978 Quasi-parallel Interplanetary Shock", J. Geophys. Res., 89, 5436, 1984, (16 pages).

C. F. Kennel, F. V. Coroniti, F. L. Scarf, W. A. Livesey, C. T. Russell, E. J. Smith, K. P. Wenzel, and M. Scholer. "A Test of Lee's Quasi-Linear Theory of Ion Acceleration by Interplanetary Traveling Shocks," J. Geophys. Res., 91, A11, 197, 1986 (12 pages).

This shock, one of the strongest accelerators observed, created an energetic proton beta of unity at the shock, indicating a reasonably efficient conversion of shock energy to energetic proton energy. The properties of the energetic particles - their spectral index and its dependence on shock strength, their spatial gradient upstream and its dependence on energy, their pitch-angle anisotropy upstream - all agreed with theory. Circularly polarized parallel propagating Alfven waves generated upstream reached an amplitude relative to the background field of 25~, in general agreement with theoretical expectation. However, the wave spectrum was in strong disagreement with quasi-linear theory, and showed evidence of cascading to high frequencies very near the shock. It appears the frontier of the shock acceleration problem is now to understand the properties of nonlinear, dispersive MHD turbulence, and how this turbulence interacts with energetic ions.

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When we look at shock systems that are smaller in spatial extent than interplanetary shocks, we often see a completely different kind of nonlinear MHD turbulence. For example, at Comet Giacobini-Zinner, Tsurutani and Smith (1986) found highly steepened, elliptically Polarized waves, with a dispersive leading edge. Similar wave forms were subsequently found at Comet Halley. These waves are given the name, "shocklet".

Shocklets were first found in the "diffuse" ion zone downstream of the leading edge of the earth's foreshock. Hada, Kennel and Terasawa (1987) have shown that at earth the diffuse ions probably do not destabilize Alfven waves with a large enough growth rate to overcome convective losses--so that the oblique shocklets cannot have been generated by the diffuse ions. Hada, et al., (1987) noted, however, that circularly polarized waves are generated at the upstream edge of the foreshock, where the "reflected" ion distribution <u>can</u> generate them by cyclotron resonant instability. They argued that the circularly polarized waves refract as they are carried into the diffuse ion zone; as they refract, they become elliptically polarized, and develop a density- compression which causes them to steepen to the observed shocklet waveforms.

Hada, T., C.F. Kennel, and T. Teresawa, "Excitation of Compressional Waves and the Formation of Shocklets in the Earth's Foreshock", <u>J. Geophys. Res.</u>, <u>92</u>, 4423, 1987.

At the invited paper at the International Rosenbluth Symposium in February, 1987, Kennel reviewed the theory of cosmic ray acceleration and the evidence for the theory in observations of solar system shocks. There are three fundamental questions of plasma physics pertinent to the theory. First - the seed particle problem: how do superthermal ions heated by the shock start to participate in the Fermi process? Second, how does the <u>nonlinear</u> interaction between energetic ions and MHD turbulence enable ions to reflect back and forth across the shock, since <u>quasi-linear</u> theory predicts no such reflection? (Most theorists just assume it occurs). Third, how to protons diffuse to energies of 3×10^{14} eV? (Quasi-linear theory predicts that they-can get to $3 \text{ X } 10^{11}$ eV, yet the regularity of the spectrum suggests the same process operates to much higher energies). Evidently, the quasi-linear theory of wave-particle scattering is inadequate and we must go to a fully nonlinear theory. Kennel also pointed out that the refraction observed to occur in the earth's bow shock will be all but inevitable in cosmic ray shocks.

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STUDIES OF NONLINEAR ALFVEN WAVES USING THE DERIVATIVE NONLINEAR SCHRODINGER EQUATION

We have been studying the evolution of weakly nonlinear, quasi-parallel Alfven waves due to self-modulation - wave-wave coupling between two Alfven waves with nearly equal phase velocities - using fluid theory. The derivative nonlinear Schrodinger equation (DNLS; Rogister, 1971, Mjolhus, 1974; Mio et al., 1976) describes such a system. The DNLS has cubic nonlinearity and quadratic dispersion, in contrast to that of the Korteweg de Vries (KdV) equation, describing evolution of oblique fast mode waves, which has quadratic nonlinearity and cubic dispersion. Using a Lagrangian technique, Kennel et al. (1988), recently pointed out that the DNLS is valid for any nonlinear system in which the underlying MHD structure consists of two waves propagating in the same direction whose speeds are close to the MHD intermediate speed. Thus, the DNLS applies to two Alfven waves which propagate parallel or at small angles to the magnetic field. In fact, Kennel et al (1988) showed that the DNLS reduces the KdV or modified KdV equations for oblique propagation angles. By using a pseudo-potential technique, we have discussed parallel and oblique stationary (equilibrium) solutions for the DNLS. Such solutions can serve as a starting point for the stability analysis of those waves, just like the monochromatic, circularly polarized Alfven waves were used for the analysis of modulational and decay instabilities.

Kennel, Buti, Hada and Pellat submitted a paper to the Physics of Fluids on the travelling wave solutions of the Derivative Nonlinear Schrodinger (DNLS) Equation.

Kennel, C.F., B. Buti, T. Hada, and R. Pellat, "Nonlinear, Dispersive, Elliptically Polarized Alfven Waves," Phys. Fluids, 31, 1949, 1988.

The DNLS describes a system of two coupled Alfven waves propagating in the same direction. A general form of its solitary wave solution was obtained, and these stationary waves were related to the appropriate fast, slow, and intermediate MHD waves. The properties of the periodic solutions were outlined. The same form also describes modulated wave packets, as well as nonlinear MHD waves.

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Hada, Buti, and Kennel submitted a paper to the Journal of Geophysical Research that expands the above treatment of periodic waves, and provides, we believe, a complete classification of the nonlinear wave solutions.

Hada, T., C.F. Kennel, and B. Buti, Stationary Nonlinear Alfven Waves and Solitons, J. Geophys. Res., 94, 65, 1989.

MIRROR WAVES IN SPACE PLASMAS

We describe our study of the mirror waves in space plasmas using numerical simulations with a two-dimensional hybrid (particle ions + fluid electrons) code. So far, we have been able to show the nonlinear consequences of the competition between mirror and electromagnetic ion cyclotron waves (ICW), both of which are driven by the same type of ion anisotropy. Numerical simulations show that, in the linear stage, the ICW grows faster due to its larger growth rate, while in the nonlinear stage, mirror waves dominate due to the relaxation of the ion anisotropy and reduction of effective growth rate for the ICW.

In a high beta plasma with a temperature anisotropy (T-perp > T-parallel), the mirror instability can be driven unstable due to the diamagnetic trapping of the ions in the wave mirror field. On the other hand, the same temperature anisotropy can also generate the electromagnetic ion cyclotron waves (ICW) via ion resonant instabilities. Both of these waves are detected in space plasma.

We have performed numerical simulations using a hybrid code in which ions and electrons are treated as discrete particles and a massless fluid, respectively, in order to study the competition between the mirror and the ICW instabilities. We carried out simulations starting with initially anisotropic ion distributions in a homogeneous plasma, and we followed the time evolution. Power spectrum analysis enabled us to identify the excited plasma waves. At the beginning of-the simulation run, the ICW grows faster than mirror waves, in agreement with the linear growth rate analysisS. However, the ions are subsequently pitch-angle scattered by the ICW and the temperature anisotropy is reduced, causing the growing ICW mode to be off-resonant, stopping further growth of the ICW. Since the growth of mirror waves is relatively insenqitive to the change of the ion temperature anisotropy, the mirror waves eventually dominate

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Publications

Hada, T., Numerical simulation of the mirror instability, Proc. of Chapman Conference on Plasma Waves and Instabilities in Magnetospheres and at Comets, Sendai, Japan, 1987.

Presentations

Hada, T. and M. Ashour-Abdalla, Numerical simulations of electromagnetic ion cyclotron and mirror waves, AGU Fall Meeting, San Francisco, December 1 986.

Hada, T., C.F. Kennel, and B.T. Tsurutani, Excitation and evolution of hydromagnetic cometary waves in a presence of the cometary rays, AGU Spring Meeting, Baltimore, 1987.

Hada, T., Numerical simulation of the mirror instability, Chapman Conference on Plasma Waves and Instabilities in Magnetospheres and at Comets, Sendai, Japan, 1987.

Hada, T. Numerical simulation of the mirror instability, AGU Fall Meeting, San Francisco, 1987.